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INVITED

OPERATION OF MULTI-MEGAJOULE INERTIAL-INDUCTIVE PULSER

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SUMMARY

The homopolar generator at the Naval Research Laboratory can store up to 4 MJ in the inductor. It has operated at 3.0 MJ level as a source of pulsed energy generated by interrupting the current in the inductor. The magnetic energy has been transferred to resistive and inductive loads using several switching modes. Using an explosively-driven breaker which generates up to 15 kV arc, 40 μsec commutation time to resistive load was achieved, with inductor-to-load efficiency of 95%. The addition of fuse switching stages was used to raise the commutation voltage to 200 kV. At this level, a current step-up transformer used as the generator load has been excited in short time (100 μsec) to generate a 0.5 MA output into a 1 mΩ load. Fast opening switches in the high-current secondary of the transformer generate high voltage pulses to provide high power output typically associated with low impedance pulse lines. A current step-down transformer was also used to generate long duration (0.2 sec) 10 kA pulses for testing of power line protection equipment.

I. INTRODUCTION

The energy storage Homopolar Generator (HPG) is a current source characterized by low voltage and broad range of current outputs. It offers the advantage of energy storage densities greater than 10 MJ/m^3. The inherent low power output of the HPG can be augmented by use of a current storage inductor and appropriate switching, to provide power output from kilowatts to terawatts[1] with energy levels to hundreds of megajoules.[2]

A system currently in use at NRL provides electrical energy storage of up to 4 MJ.* It uses staged[3] opening switches for power amplification and meets various user requirements either by direct coupling to the test load or by means of current transformer coupling. Pulse widths from seconds to microseconds have been delivered to various loads, with routine output of 10^{10} W. The scaling of present performance indicates feasibility of operating the system at 10^{12} W.

II. STORAGE OF ENERGY

Various elements of the NRL Homopolar Generator/Inductive Storage system have been described previously[3,4]. Summarized details and previously unreported performance are discussed here.

The inertial-inductive system is shown schematically in Fig. 1A and its photograph is shown in Fig. 1B. Initially the energy is accumulated in two counter-rotating rotors made from beryllium-copper forgings machined into a constant stress configuration. Each rotor is 58 cm diameter, weighs 82 kilograms and stores 5.1 MJ inertial energy at 18,000 rpm. Stress in the rotor at this speed is approximately 5.9 x 10^9 dynes/cm^2. The specific energy stored is 65 J/gram. The rotors are contained in partially evacuated fiberglass housing to reduce windage loss. Each wheel is driven by a 24 HP hydraulic motor which is capable of accelerating the wheel at a rate of approximately 2,000 rpm/min. The rotors, the motors and housing form a self-contained package which is located within the excitation/energy storage coil.

*The maximum stored energy increases to 7 MJ when the inductor resistance is reduced by cryogenic cooling.

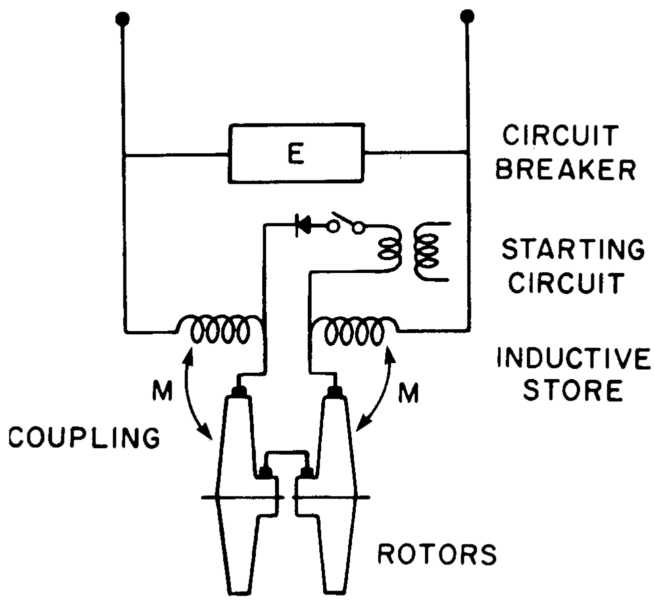

Fig. 1A. Schematic presentation of the inductive charging circuit for the NRL self-excited inertial/inductive store.

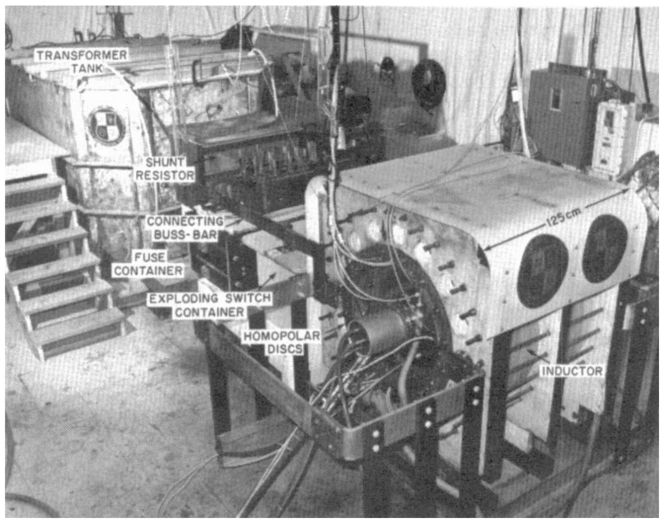

Fig. 1B. View of the TRIDENT I System showing the physical layout of the system megampere current tests.

The coil shown in Fig. 1B consists of 1700 kg, 7.6 cm high and 1 cm wide copper conductor mounted on edge in a single layer of 42 turns. Internal diameter of the coil is 1 meter and d.c. inductance is 1.4 mH. The magnetic field at the center is 40 kG for a 100 kA current. Coil insulation for surface flashover has been tested to withstand at least 200 kV.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1981**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Operation Of Multi-Megajoule Inertial-Inductive Pulser**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory, Washington, DC 20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**6**	

The coil is electrically connected to each of the outer rims by thirty-six brushes, each containing 4224 tinned-copper wires of 0.015 cm diameter. The inner hubs of the two rotors are connected electrically using solid copper-graphite brushes.

Electrical discharge is started by providing the storage coil with an excitation current of approximately 700 A from an external 60 Hz (rectified) transformer; then both sets of brushes are lowered pneumatically to contact the wheel and the circuit is completed via a circuit breaker denoted with a symbol E in Fig 1. Outer brushes have been operated at a peripheral velocity of 475 m/s. Their lifetime, current density capability and other characteristics are discussed in Ref. 5.

The conversion of mechanical to electrical energy is determined by rotor speed, rotor-to-inductor coupling and inductor resistance. For example, with 7.5 MJ of energy stored inertially, the magnetic energy transferred to the inductor is 2.7 MJ giving an inertial to inductive efficiency of 36%. The maximum operating current to date is 60 kA with a risetime of approximately one second. Not all the energy in the inductor is available for transfer to a load since the rotor traps part of the magnetic flux. For fast discharge (<1msec) of the system, approximately 30% of the electrical energy is trapped by the rotor.

III. SWITCHING

Efficient transfer of energy from a storage inductor to a desired load depends upon the availability of switches which can carry the HPG current for seconds, then open in the shortest possible time, generating arc voltages sufficient to transfer stored current to a specified load. These switches must, finally, hold off inductively generated voltages which may range up to hundreds of kilovolts, depending on the application. At present, there is no single unique switch which can satisfy these requirements. Thus a multi-stage switch comprised of separate slow opening and fast opening components developed previously[6] has been incorporated in this energy storage system. The number of switching stages and switch characteristics are dictated by output requirements.

A. Explosively Actuated Circuit Breaker (EACB): First Stage

The staged switching concept used in the HPG/Inductive Storage System was previously developed in the TRIDENT I system.[7] Switches based on this work are capable of interrupting currents in the megampere range, while holding off inductively generated voltages of 10^6V, with recovery time of approximately 40 μsec. The EACB used as the first stage is a single-shot current interrupter similar to that used by Glukhikh, et al[8] and developed to its present state at NRL[9]. It consists of a tubular current conductor filled with a paraffin tamper and a small explosive charge. Since the EACB must carry current for seconds, resistive heating may lead to melting of the conductor. Thus, dimensions of the conductor are chosen so that this does not happen. A relation between the current pulse and the temperature of the conductor can be estimated from the known physical constants of the conductor. If the heating rate in the metal is equated to the rate of rise of internal heat, a relation between conductor temperature T (relative to room temperature T_R) and the current pulse is obtained:

$$\int j^2 \, dt = \int_{T_R}^{T} (C_v/\rho) \, dT \qquad (1a)$$

where j is current density, ρ is the resistivity and C_v is the heat capacity per unit volume. For an aluminum conductor having a melting temperature of 658° C, evaluation of the right side of this equation yields an upper useful limit of

$$\int j^2 dt = 2.7 \times 10^{16} \ A^2 \ sec/m^4 \qquad (1b)$$

In the NRL system, an aluminum switch conductor, having an outer diameter of 6.3 cm and 0.16 cm wall thickness, has been selected as the standard EACB conductor due to its availability and ease of fabrication. It has been determined from the above calculations that 50 kA peak is the maximum safe operating current for a single switch. Experimental confirmation of this value indicates that possible heat losses during current flow period are negligible. Above this current, two parallel switches are used. The upper limit of metal thickness is also adjusted so that metal vaporization occurs soon after predetermined switch opening time. This is used to advantage since one of the potential problem areas in system operation involves the possibility that a switch fails to operate. In such an event, either the HPG brushes would lift while current is flowing, or wheel reversal would occur. In either case the result would be the destruction of brushes and possibly brush actuation springs. Using the conductor melting criterion above, dimensions of a tubular conductor can be selected so that the first stage switching is essentially lossless in normal performance, and yet the tube may be used as a safety fuse in the event of a "misfire" fault.

Electrical performance of the EACB is characterized by arc voltage, opening time and recovery voltage. The switch utilized in the NRL system generates an arc voltage of approximately 300 V/cm length during its 30 μsec opening time and is capable of sustaining this voltage during the time current flows through it. During switch testing, the current flow has been as long as (e-fold decay) 5 msec, resulting in deposition of about 1.3 MJ of energy in the switch. If a low impedance load circuit such as a fuse or sub-Ohm resistor is connected across the switch then the paraffin pusher within the switch quenches the arc, transferring current to the load with electrical efficiency greater than 95%, and the switch is then capable of hold off of more than 10 kV/cm after only 40 μsec recovery period required for cooling of the arc. Such EACB characteristics allow it to be used in the Inertial/Inductive Storage System either as a nearly lossless component to drive low impedance loads including reistors and transformer primaries, or to transfer stored current to a second opening switch stage, typically a wire or foil fuse.[1]

B. Fuses: Voltage Steepening Stages

Use of fusing elements in an inductive storage system to interrupt current is well understood in terms of scaling[10] and in terms of the effects of the medium that surrounds the fuse on its electrical characteristics[11,12]. Their application in the inertial-inductive storage system is needed primarily to raise the inductive voltage required for fast commutation of the inductor current to a high impedance load.

To optimize current transfer in the inertial-inductive circuits discussed in the following section, techniques were developed to reduce energy dissipation in the fuse and to shape the voltage waveforms developed by the fuse. In inductor-to-inductor transfer, such as that shown in the circuit of Fig. 2, (utilizing a current step-up transformer), at least 50% of the energy stored in the inductor must be dissipated in the transfer element.[13] Large explosive forces are generated when multi-megajoules pulsers are used. By inserting a large volume resistive element in parallel with the fuse, up to 60% of the energy to be dissipated in the transfer can be absorbed in the resistor at low energy density. To determine the value of the shunt resistance and appropriate lengths of the fuse, an analysis of the energy partition was carried out. With the roles of dissipating energy and developing voltage being shared by fuse and parallel resistor, the procedure for selecting an appropriate combination becomes complex. As a first step in developing such a procedure, the energies dissipated by the two component elements are investigated. The resistances of each element is called R_1 (for fuse) and R_2 (for shunt resistor), and W_1 and W_2 are the energies dissipated in them. Being connected in parallel, these resistances necessarily have the same voltage impressed across them. As a consequence, their electrical power dissipation (dW_1/dt and dW_2/dt) is related by

$$R_2 \frac{dW_2}{dt} = V^2 = R_1 \frac{dW_1}{dt} \tag{2}$$

If R_1 is a time varying resistance (fuse), then the energy delivered to the parallel fixed resistor, R_2 is

$$W_2 = \frac{1}{R_2} \int_o^t R_1 \frac{dW_1}{dt} dt = \frac{1}{R_2} \int_o^{W_1} R_1 dW_1 . \tag{3}$$

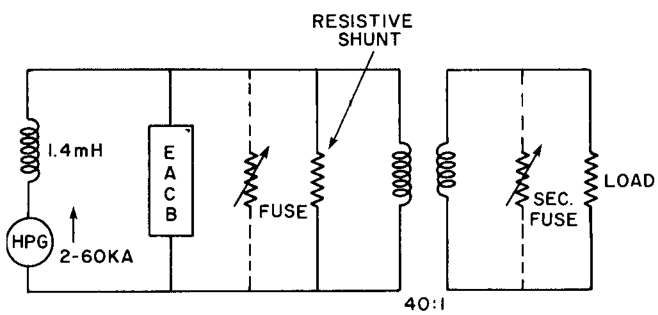

Fig. 2. Experimental circuit used for evaluating the feasibility of generating terawatt power pulses using an inertial/inductive store system.

The energy taken from the circuit and dissipated in the switching is the sum of $W_1 + W_2$. By rewriting the energy in the fuse in terms of its dimensions (length H, and cross-section S) and its energy density, w, an expression (in brackets, Eq. 4) analogous to fuse energy of single element analysis is obtained (for resistivity, ρ , associated with a specific fuse material):

$$W_2 + W_1 = \left[\frac{H}{R_2 S} \int_o^w \rho(w)\, dw + w \right] HS . \tag{4}$$

Defining the final fuse energy density, w_F, and calling the bracketed expression, w_D , when the upper limit is w_F, the partition of energy[9] between the fuse and the shunt resistor is determined by the parameter H/SR_2 . Larger values of this parameter correspond to a greater share of the energy being dissipated in the fixed resistance R_2 .

The extension of this analysis[14] includes an expression for the variation of fuse energy density to obtain peak voltage. The above analyses are based on the assumption that the fuse resistivity is a unique function of the energy deposited in the fuse and does not depend on the rate of energy delivered to the fuse This was checked experimentally using different values of shunt resistors for given stored energy. Fig. 3 shows the considerable effect of the shunt resistance on the resistivity of the fuse. Fuse parameters are shown in Table 1. This data is used to correct the predictions based on the analysis given above, in determining fuse length and cross-section for desired values of the primary voltage.

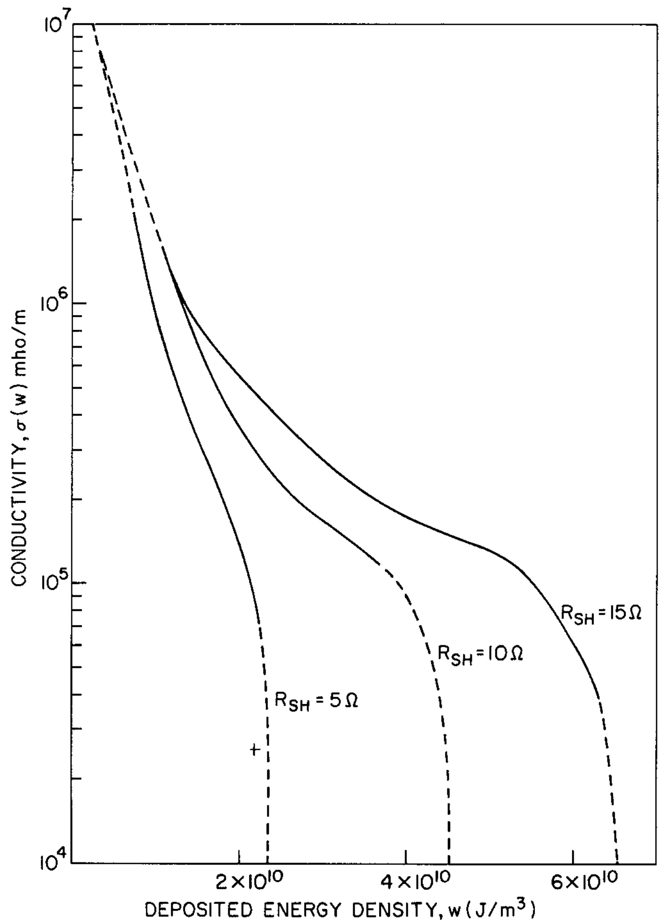

Fig. 3. Fuse conductivity dependence on deposited energy density in the fuse. Conductivity is shown to be a function of the current diversion from the fuse as determined by the value of a parallel shunt resistance.

(R_{sh} = 5Ω)	#18 wire Cu	$S = 8.23 \times 10^{-7} m^2$
		$H = 1.472$ m
		$i_{max} = 28.2$ kA
		$V_{max} = 94.9$ kV
(R_{sh} = 10Ω)	#19 wire Cu	$S = 6.527 \times 10^{-7} m^2$
		$H = 1.472$ m
		$i_{max} = 24.8$ kA
		$V_{max} = 139$ kV
(R_{sh} = 15Ω)	#19 wire Cu	$S = 6.527 \times 10^{-7} m^2$
		$H = 1.472$ m
		$i_{max} = 25.8$ kA
		$V_{max} = 153$ kV

Table 1

Fuse parameters used in evaluating effects of fuse/resistor parallel current sharing

The second technique associated with primary switching was the optimization of the shape of the voltage pulse generated by the primary switch. By dividing the fuse length into two sections with different cross-sectional area, the pulse width has been increased by a factor of two. This helps to increase the current rise-time in the secondary of the transformer (Fig. 2), resulting in more efficient energy transfer. Fig. 4 provides the fuse parameters required to achieve output voltages in 100-200 kV range.

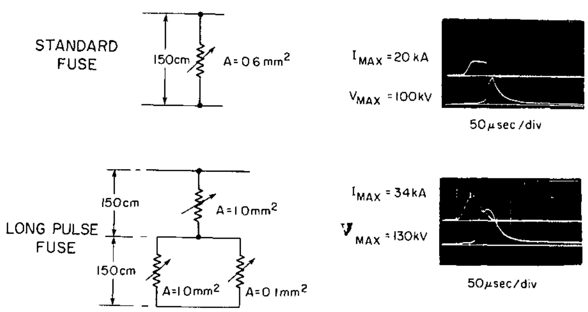

Fig. 4. Effect of a delayed fuse stage on current and voltage waveforms when current from an inductive store is transferred to an inductive load.

IV. APPLICATIONS

Operating experience gained with the NRL HPG/ Inductive Store, including the development of special switch characteristics, has shown that the system is well suited for generating long time (millisecond) as well as short time (microsecond) power pulses. Examples of two applications demonstrating both types of output are discussed below.

A. Long Duration Output

To satisfy requirements for testing surge arrestor devices for protection of power lines and equipment against sustained high (10 kA) current, the HPG current source was used in conjunction with current step-down transformer* to provide L/R time of more than 0.2 sec. The surge arrestor contains a spark gap in series with a variable resistor with initial value of about 0.1Ω. This requires an initial voltage of 2 kV to produce gap breakdown.

Fig. 5 shows the circuit which provides the required output. The current decay time is determined not only by the load resistance but also by the accumulation of resistances in the HPG inductor of 2 mΩ, and primary and secondary resistances of 1.3 and 24.6 mΩ, respectively, for the transformer with primary (26 turns) to secondary (140 turns) ratio of 5.4. The leakage inductance of 97 μH and high primary (3 H) and secondary (80 H) inductances are obtained by use of iron laminations with 80V-sec characteristic. The transformer has been hi-potted to 10 kV. The various stray capacitances are 27.3, 6.4 and 8.7 nF for primary to secondary and primary and secondary to core, respectively. The total weight of the transformer is 22,600 lbs.

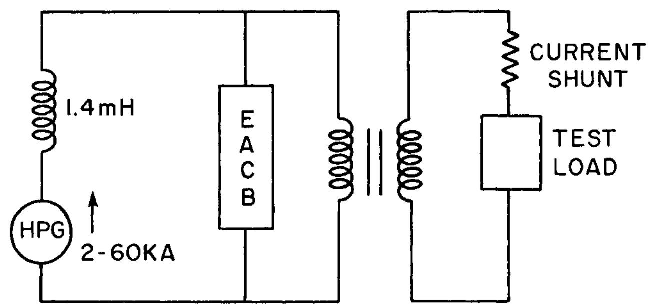

Fig. 5. Experimental circuit for driving a 0.1Ω test load at 10 kA current with an e-folding time greater than 250 msec.

Testing was performed with inductive energy store of 2.7 MJ and approximately 1 MJ delivered to the test load. The output pulses delivered to the surge arrestor depended on the specific behavior of the arrestor. The pulses delivered across a short circuit load characterize the HPG- transformer as a current source with peak current of 10 kA (for 54 kA in the primary) and a rise-time of about 100 μsec. The current decay time, i.e., the e-folding time is 0.2 sec., providing one of the longest sustained high current surges into relatively high impedance loads.

B. High Power Output

The HPG storage system and opening switches developed for use in conjunction with formation of large energy pulses** were also adapted to production of sub-microsecond pulses at high power level and with good system efficiency. Initial experiments

*Designed by Clarence Controls, Inc., Buffalo, N.Y. and fabricated by Niagra Transformer, Inc.

**Use of opening switches to generate 100 μsec pulsed output is discussed in Ref. 16.

demonstrating the use of a current step-up transformer to convert 60 kA HPG current into megampere currents have been completed. Fig. 2 is the circuit of the TRIDENT II pulser employing the HPG with an air core transformer. Shown in Fig. 6, is that transformer. Its secondary provided an inductor storage for driving a load. The performance of the system with short circuit and 1.0 mΩ loads is discussed in Ref. 15. This reference includes the analysis of the effects of circuit parameters on current multiplication and power transfer, and provides a detailed description of the transformer.

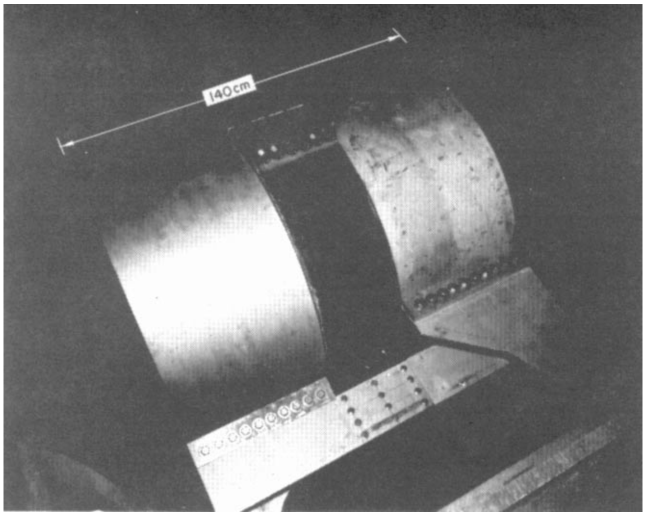

Fig. 6. Two-turn current step-up transformer used in delivering megampere current to a test load from an inductive storage coil charged to tens of kiloamperes.

The function of the opening fuse stages in the transformer circuit of Fig. 2 is to increase power available for the load. Fig. 7 shows transformer secondary currents for short circuit conditions and for reduced currents resulting from added switch and load inductance. Ordinarily, energy delivered to the load would be reduced significantly at the lower currents. However, in this application using fuse switching, losses due to circuit inductance are compensated for by the reduction in fuse vaporization energy. Switch test configuration may, therefore, be modified as needed without seriously altering test results. The overall efficiency at output level potentially at 500 kV is about 6% at low energy and increases to 10% at higher energy.

A single stage aluminum foil fuse 12.7×10^{-3} cm thick and measuring 40 cm wide by 30 cm long has been tested at the level shown on Fig. 7. It produces an open circuit voltage of 75 kV with rise-time of 5 μsec. at a current of 0.25 MA. These parameters are similar to those of TRIDENT I[7], where feasibility of generating Terawatt pulses was demonstrated. However, these preliminary tests showed that the JxB forces associated with transformer and fuse currents damaged the foils before vaporization occurred.

A new switch assembly which re-orients the foil fuse in the transformer field and adds capability for a second stage wire fuse array has been added. Initial testing of this array indicates that foil reaches vaporization in a repeatable manner, producing a consistent 75 kV across the open circuit fuse. Calculations indicate that 2-4 MJ system energy will be sufficient to drive this array to at least the 1 MV level.

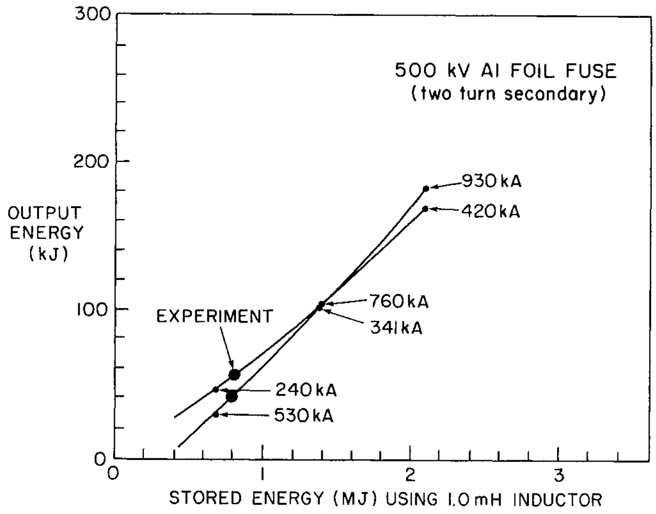

Fig. 7. Effects of switch and load inductances on output energy from the TRIDENT II transformer where exploding foil fuses are used in pulse generation.

V. CONCLUSIONS

Operating experience with the NRL inductive/inertial energy store has shown that (with available staged opening switches) it is a viable alternative to capacitive systems for many megajoule level pulse power applications. The capability of supplying current to a load directly from the storage coil, or driving the load at kiloampere to megampere levels using only switching and transformers makes this type of system particularly versatile as a laboratory test bed. In addition to fulfilling user requirements, it can also be used for testing tradeoffs and developing performance data for improving energy transfer efficiency. Components similar to those used for this system, including inertial store, inductive store, and switching have performed individually at both lower and higher levels of performance. Consequently, it is expected that this system can be scaled upward to tens of megajoule storage levels either directly or by paralleling similar systems.

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